High-Fidelity Finite-Element Structural Acoustics Modeling of Shallow-Water Target Scattering

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LONG-TERM GOALS

The goal of this three-year effort is to develop a state-of-the-art, high-fidelity, finite-element, broadband computer simulation capability for modeling the scattering of sonar signals by undersea mines located in or near the seabed in littoral environments with smooth or rippled water/sediment interfaces. The target models will include all internal and external structural details that significantly affect the scattered field.

OBJECTIVES

The primary objective is to provide the U.S.Navy with a state-of-the-art MCM simulation tool, readily available to scientists at any laboratory, on virtually any computer platform, at modest cost. A secondary objective is to maintain a continuing R&D effort in order to significantly increase the computational efficiency of the software, thereby expanding the ability to model more complex targets, at higher frequencies and over broader bands.

APPROACH

- **High fidelity**

To achieve high-fidelity models of elastic-wave propagation in a mine, the models employ 3-D continuum mechanics for every part of the mine. Thin structural components, such as plates and shells, are modeled with 3-D elasticity theory, rather than plate or shell theories (the latter being 2-D physics inside 3-D geometry). This use of 3-D elasticity for thin structural components, rather than the traditionally and universally used plate and shell theories, is a special feature of this project. Burnett has had extensive and very successful experience since the mid-1980s developing large FE codes based on this 3-D physics philosophy [1,2].

- **Broadband**

Target insonification is virtually always a pulse, yielding a broadband time-series response. For a variety of reasons, the modeling is being done in the frequency domain, i.e., CW. A frequency sweep must therefore be performed, over typically several hundred frequencies, followed by an inverse FFT to produce the time series. To enable this process to be performed in a timely manner, two approaches are being pursued concurrently. One is the development of mathematical and modeling techniques to make each frequency analysis run as fast as possible. The other is the use of distributed processing at a High Performance Computing center, which will enable hundreds of frequencies to be analyzed in about the same time as one frequency.

- **High reliability**

The control of errors, via verification and validation ("V&V"), plays a key rôle in this project; it is essential to the goal of providing reliable simulations of the real world. Verification refers to the control of errors in the finite-element solution vis-à vis the exact solution of the idealized mathematical model, i.e., computational/mathematical errors. Validation refers to the control of errors in the exact solution of the idealized mathematical model vis-à vis the real world, i.e., errors in the physical asumptions and data in the idealized model. V&V is an ongoing, never-ending exercise as the simulation capabilities mature.

WORK COMPLETED

All of the finite-element modeling described below, with the exception of work done at HLS Research and N.C. State, was done at NSWC-PC using the commercial finite-element code COMSOL Multiphysics (www.comsol.com), referred to as simply Comsol below.

- **Modeling techniques developed:**

  - **Scattering from buried targets**

A technique was developed for modeling scattering from a target buried in a "sediment", modeled as a fluid with different properties from those of the fluid above (Fig. 1). The challenge here was to apply radiation boundary conditions (RBCs) on the outer boundary of the computational domain that are appropriate for two different fluids.

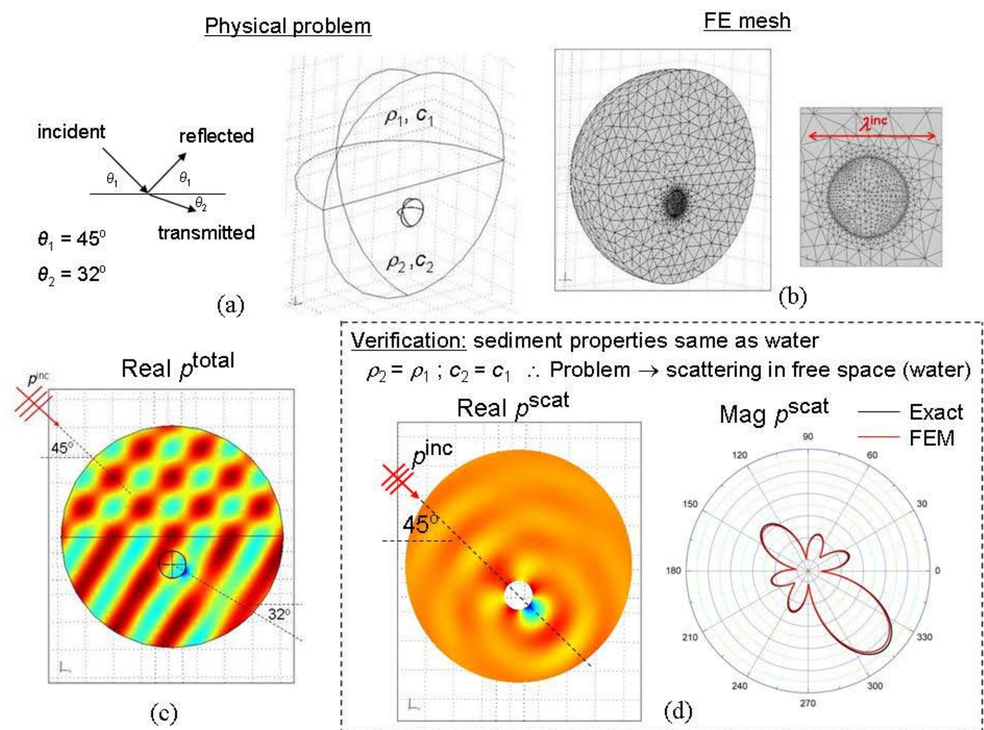


Figure 1. Scattering from a buried spherical steel shell. (a) the physical problem, (b) FE mesh, (c) contours of real part of total pressure, (d) verification by comparison with the exact solution when the two fluids have the same properties

  - **New radiation BCs, which reduce size of computational domain**

NSWC-PC has developed a new mathematical formulation for RBCs that can be applied to spheroidal and ellipsoidal boundaries of the computational domain, permitting the latter to more closely circumscribe high-aspect ratio targets (Fig. 2). This work will be published.

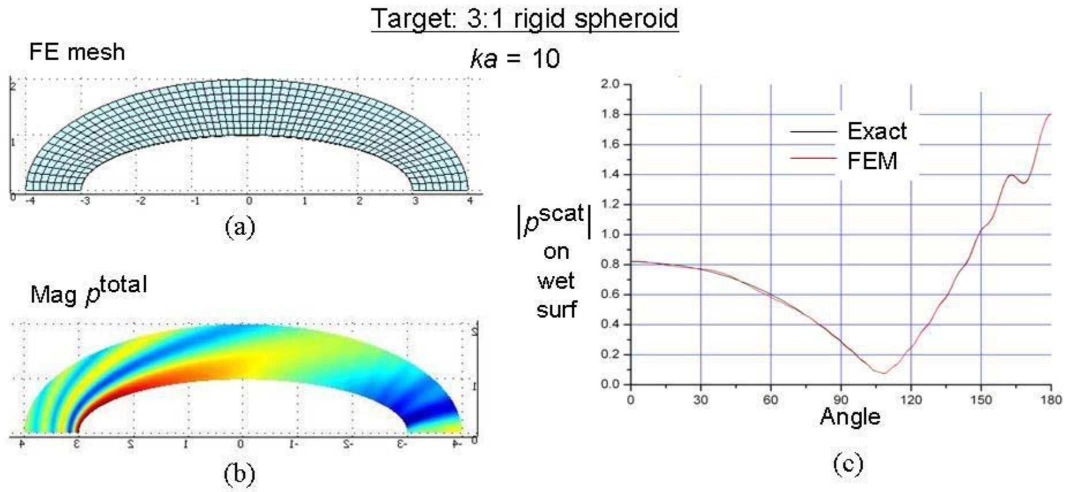


Figure 2. Verification of new RBCs. (a) FE mesh for water surrounding a rigid prolate spheroidal target, (b) contours of magnitude of total pressure, (c) comparison of FE and exact solutions.

- **Decomposition of incident field, which reduces size of computational domain**

When the target and environment have planes of symmetry, the model can be cut in half (or quarter or eighth) and any asymmetric incident field can be decomposed into symmetric and antisymmetric parts (Fig. 3). This typically speeds up a 3-D analysis about 3x for each plane of symmetry.

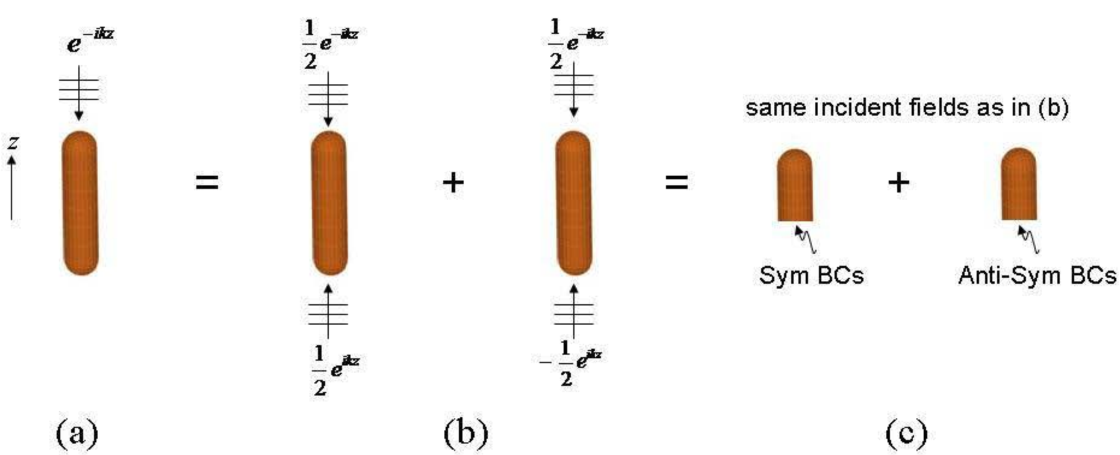


Figure 3. Reduction of problem. (a) the original problem, (b) decomposition into two equivalent problems, (c) reduction of the two problems in (b) using symmetric and anti-symmetric BCs.

- **Parametric sweeping: over frequency and along track of source**

The Comsol code can automatically sweep over any user-specified parameter (Fig. 4).

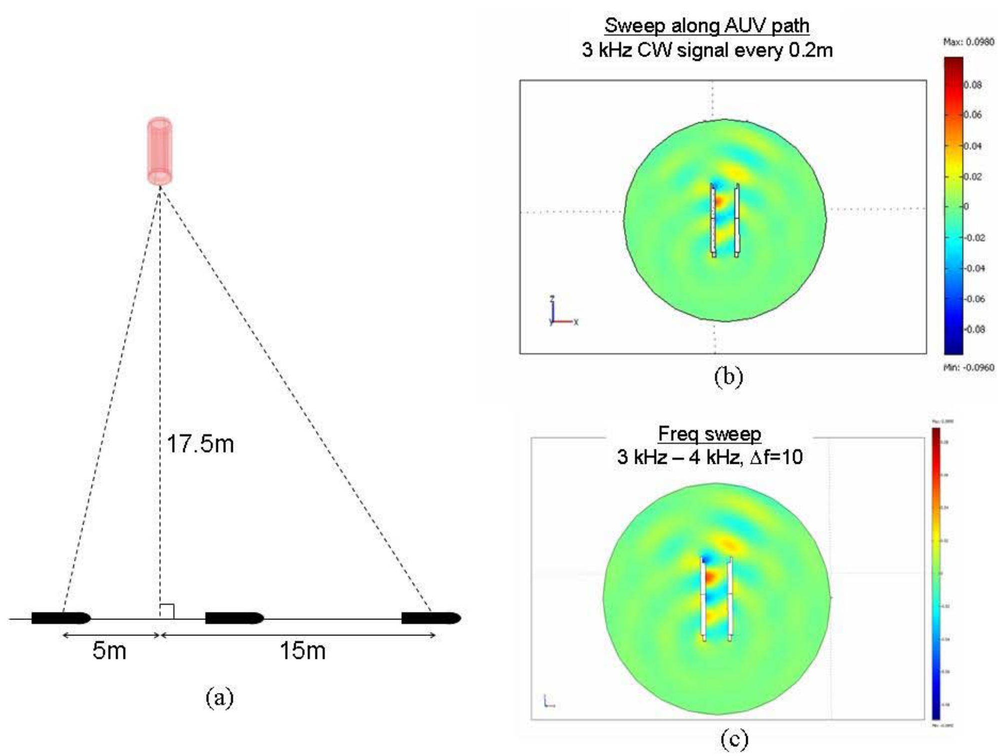


Figure 4. (a) Insonification of a concrete conduit pipe by a source moving along a straight path, (b) animation (not shown) of sweeping along the path, (c) animation (not shown) of a frequency sweep.

- **Evaluation of scattered field exterior to the FE mesh, using Helmholtz integral**

The scattered field is usually wanted at points or along a track that lie outside the FE mesh. This can be computed quickly using the classic Helmholtz integral, which uses the same 3-D physics as the Helmholtz PDE inside the mesh (Fig. 5).

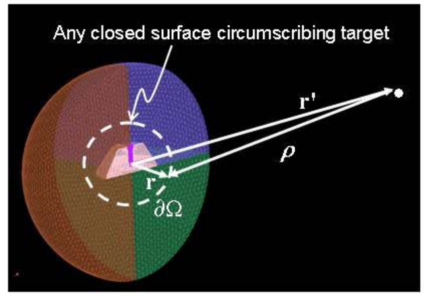
Theory

$$p(\vec{r}') = \iint_{\partial\Omega} \left(\frac{\partial G(\vec{r}',\vec{r})}{\partial n} p(\vec{r}) - G(\vec{r}',\vec{r}) \frac{\partial p(\vec{r})}{\partial n} \right) d\Gamma$$

$G(\vec{r}',\vec{r}) =$ Green's function

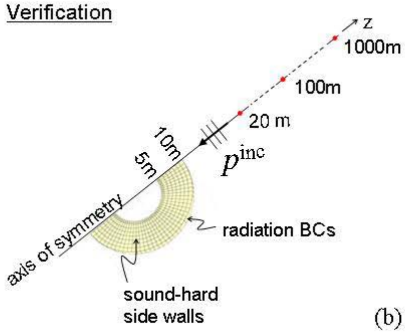
$= e^{-ik\rho} / 4\pi\rho, \quad \rho = |\vec{r} - \vec{r}'|$

for free field



(a)

Verification



$|p^{scat}|$

z	exact	Helmholtz
20	.446	.445
100	.0872	.0869
1000	.00860	.00857

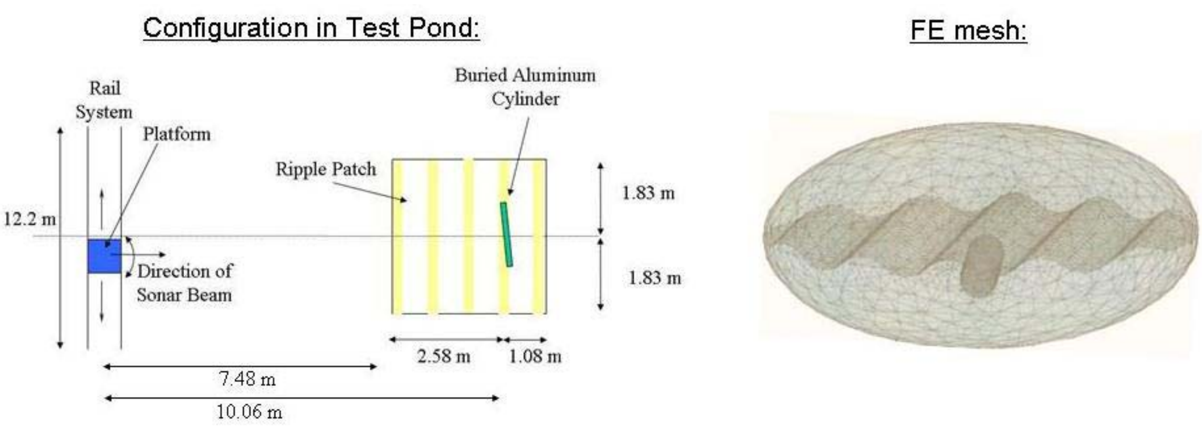
(Same accuracy as in FE solution in mesh)

(b)

Figure 5. (a) The Helmholtz integral and graphic depicting how it is used, (b) verification by comparing with exact solution for scattering from elastic spherical shell.

- **Targets buried under ripples**

Work in progress: modeling a target buried under a ripple patch (Fig. 6).



(a) (b)

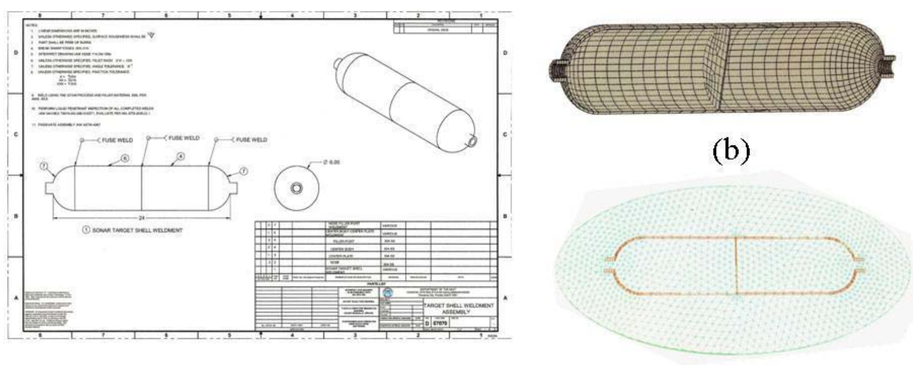
Figure 6. Configuration of an experiment performed in the NSWC-PC test pond, (b) Comsol mesh of aluminum cylinder under the ripple patch.

- **Preparations for distributed processing at High Performance Computing center**

NSWC-PC has established accounts for Burnett, Sammelmann and Kwang at the HPC center at Wright Paterson Air Force Base. The center has clusters of, e.g., 2048 processors, which will provide this work with large-scale distributed processing, enabling frequency sweeps over several hundred frequencies to be performed in about the same time as a single frequency. As soon as licensing agreements can be negotiated with Comsol, modeling can begin.

- **Design and fabrication of new target, for code validation**

A new target has been designed and fabricated (Fig. 7). It incorporates several "generic" physical features often found in mines, e.g., internal partition with different materials on either side and external protrusions. Dimensions and material properties will be known to a relatively high precision, which is necessary for validation modeling.



(a) (c)

Figure 7. (a) Engineering drawing of target, (b) FE mesh of target, (c) FE mesh of target and internal and external fluid.

➢ **Collaborations:**

- **with APL/UW and NUWC**

The Broadband Mine Classification (BMC) program has defined 4 Scenarios for which there exists good experimental data (Fig. 8). NSWC-PC has provided FE model data, verified vis-a-vis exact solutions, to APL/UW and NUWC for Scenario 1 (Fig. 9). Models have been prepared for Scenario 2 (Fig. 10) and will be ready as soon as the above Helmholtz integral technique is extended to the proud environment.

Scenarios for FEM Data Generation

	Range	Object	Bottom	Laydown	Depth	AUV Height	Frequency Range	AUV Path
Scenario 1: tank	1 m	sphere	NA	NA	free field	NA	1 - 12 kHz	circle
Scenario 2: SAX04	17.4 m	pipe	sandy	proud	20 m	3.9 m	3 - 4.5, 6 - 11, 13 - 27 kHz	line*
Scenario 3: NRL Ocean, rock	100 m	rock	sandy	proud	11 m	4 m	1 - 10 kHz	circle
Scenario 4: NRL Ocean, Mk 36	100 m	Mk 36	sandy	proud	11 m	4 m	1 - 10 kHz	circle

* AUV follows a straight line path 20 meters long transitting across aspect angles from about -15 degrees to 0 degrees (end on) to 35 degrees. Closest approach to object is 17.4 meters.
Note: Pings are linear chirps over the ranges listed.

Figure 8. Description of 4 Scenarios used for BMC modeling

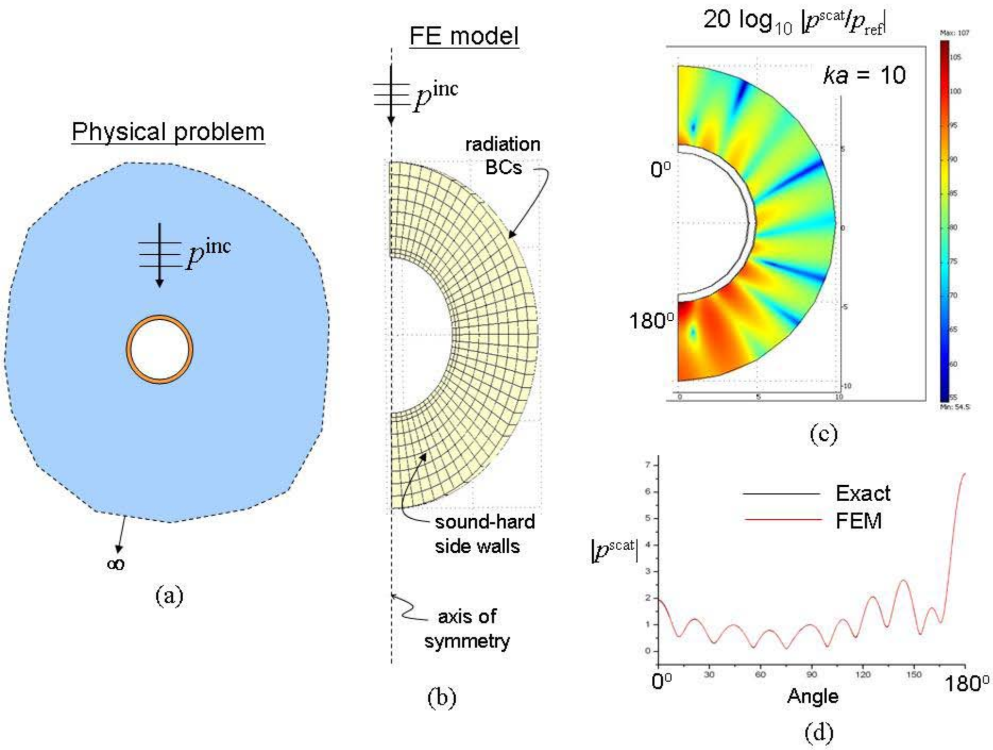


Figure 9. Model for Scenario 1. (a) the physical problem, (b) FE mesh, (c) contours of computed intensity of scattered field at ka = 10, (d) verification vis-a-vis exact solution.

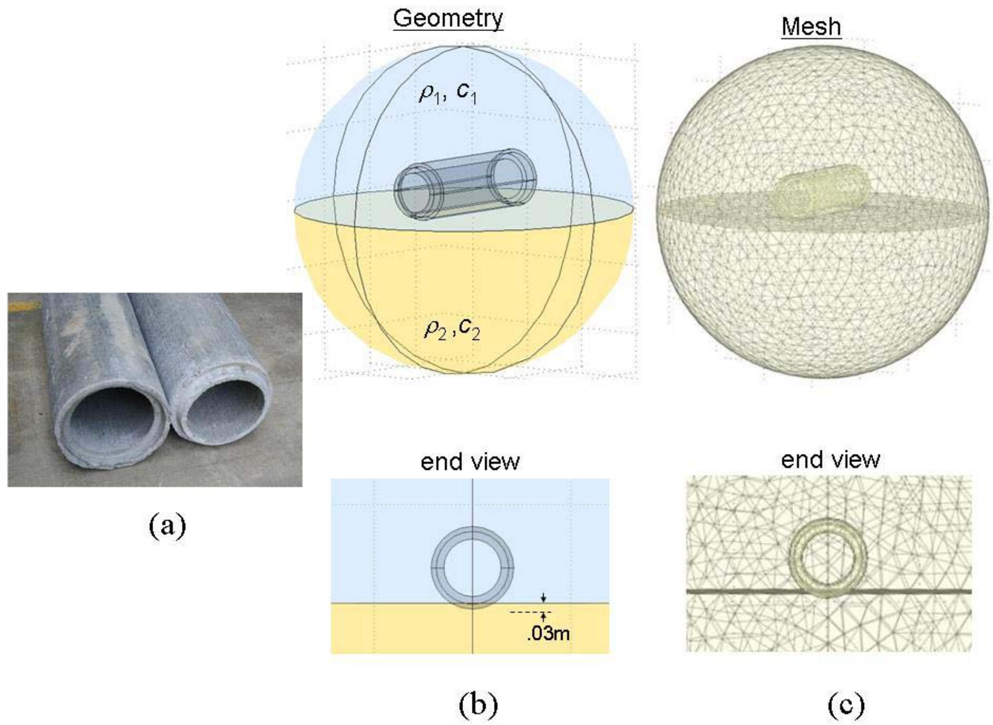


Figure 10. Model for Scenario 2. (a) photo of real concrete conduit pipes, (b) geometry of FE model for a pipe slightly buried in sediment, (c) FE mesh corresponding to the geometry.

- **with HLS Research**

Also for the BMC program, NSWC-PC is working with HLS Research to couple data from NSWC-PC's Comsol target scattering models with HLS's littoral propagation code SLaMM, which is based on a virtual source technique. Comsol is used to generate Green's function matrices for the target; those matrices are sent to HLS for insertion into SLaMM (Fig. 11). This technique has been verified for a 2-D problem of scattering by an infinitely long solid elastic cylinder (Fig. 12). The exact solution was developed by NSWC-PC.

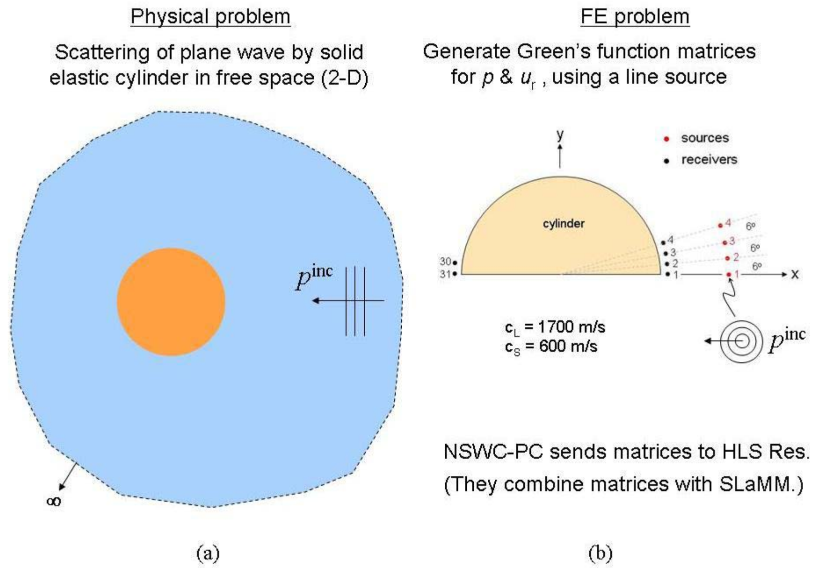


Figure 11. Collaboration with HLS Research. (a) the physical problem, (b) modeling technique for computing Green's function matrices.

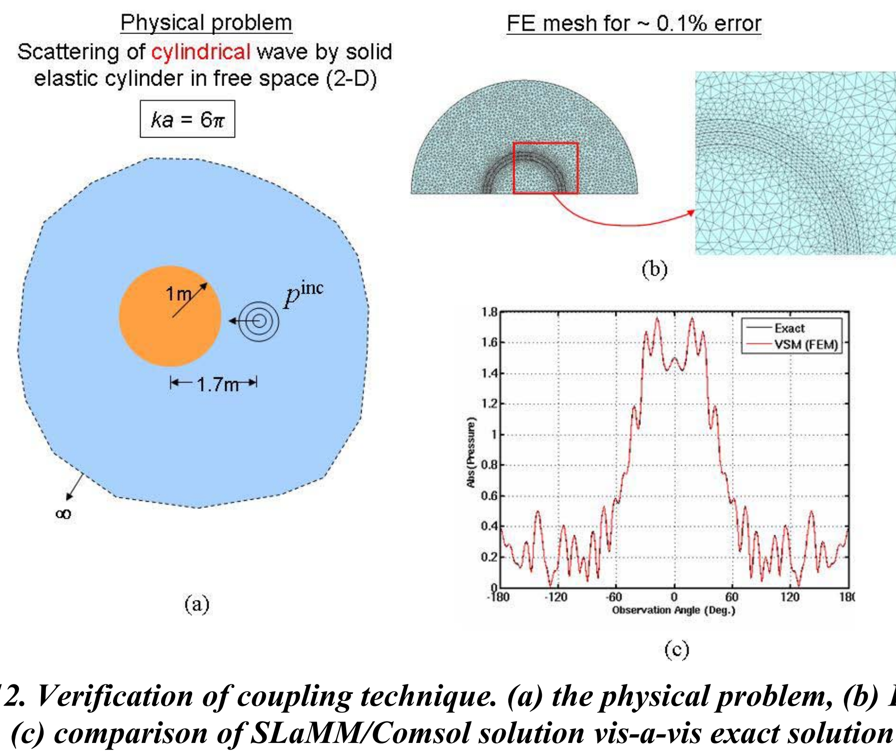


Figure 12. Verification of coupling technique. (a) the physical problem, (b) FE mesh, (c) comparison of SLaMM/Comsol solution vis-a-vis exact solution

- **with N.C. State**

Prof. Kazufumi Ito and Dr. Jari Toivanen have been working part-time in the project since the beginning of 2006. In the end of July, 2006, Dr. Zhonghua Qiao (zqiao@ncsu.edu) started to work in the project as a postdoctoral researcher.

A two-dimensional finite element code for scattering by elastic targets and rippled sediment has been developed using Fortran. The iterative solution procedure uses a domain decomposition preconditioner which is based on a fast direct solver. The diameter of the computational domain can be be several hundred wavelengths. Typically solution requires from a few seconds to a couple of minutes depending on the size of the problem.

Solution techniques have been developed for more general layered media. These techniques are suited for seabeds with large slopes or variations and also for water columns with stratified properties.

The basic idea is to construct Schwarz-type multiplicative-domain decomposition preconditioners and to perform a domain embedding in subdomains so that a fast direct solver can be used. Numerical experiments with two-dimensional and three-dimensional problems have confirmed the efficiency of the developed techniques.

For two-dimensional problems, a code coupling the Fortran solvers for the far-field part of the computational domain and Comsol Multiphysics finite-element modeling software for the near-field has been developed. The coupling is done using Matlab which calls the Fortran and Comsol routines. This code demonstrates that the Comsol and Fortran routines can be coupled with reasonable effort. The same approach can be used also for three-dimensional problems. Comsol can be used in the modeling of complicated scatterers while it cannot solve scattering problems in acoustically large domains for which the Fortran solvers have been developed.

Currently a general finite-element code for three-dimensional scattering problems in littoral environments is under development. The generation of suitable meshes for the near-field part of the domain requires some effort as Comsol's current mesh generator has some limitations in the case of three-dimensional domains. The methods developed for two-dimensional cases can be generalized in a straight forward manner for three-dimensional problems, but still implementing them in this case requires considerable effort.

Numerical experiments with a test setting used by Joe Lopes for measurements in the test-pool at the Naval Surface Warfare Center, Panama City, FL, are being carried out currently. The aim is to compare the measurements with the numerical results.

RESULTS

In FY05 Burnett decided to use the commercial finite-element code COMSOL Multiphysics (then called FEMLAB) for modeling target scattering. It appeared to have the essential physics capabilities and finite-element techniques for this kind of work. Now, at the end of FY06, it is clear that the code has admirably fulfilled its promise, performing well beyond initial expectations. It is an excellent platform for both R&D and production modeling, making possible all the research advances and modeling results described above. Looking ahead to FY07 and beyond, and considering R&D currently underway, it seems reasonable to expect that the code will be able to handle essentially all the modeling required on these ONR programs.

IMPACT/APPLICATIONS

This 3-D target scattering simulation capability will be an important component of acoustic MCM systems developed for, e.g., SWAMSI, BMC, SAX04 and SERDP, since the reliability of D&C algorithms depends significantly on the accuracy of predicted signatures of targets of interest. The scientific impact will be all the modeling techniques developed, which should be useful in other DoD programs as well as in the general structural acoustics community.

RELATED PROJECTS

- SERDP (Strategic Environmental Research and Development Program)

Assessing Sonar Performance Against Underwater UXO. Apply littoral target scattering modeling tools described herein to underwater UXO, focusing on characterization and remediation of UXO-contaminated environments.

- IAR (Independent Applied Research)

Detection and classification of MLO. Apply littoral target scattering modeling tools described herein to investigate D&C using cooperative, multi-vehicle UUV systems, with emphasis on impulse excitation at close range to excite LF resonances.

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[1] D. S. Burnett and M. Zampolli, “FESTA: a 3-D finite-element program for acoustic scattering from undersea targets”, NATO Undersea Research Centre report,
SR-394, 2004.

[2] D. S. Burnett, “VISTA: Vibrations due to the Interaction of Structures and Acoustics”, Theory Manual, Version 3.2, Dec. 1992, AT&T Bell Laboratories, sponsored by DARPA.

PUBLICATIONS

[1] K. Ito and J. Toivanen, A Fast Iterative Solver for Scattering by Elastic Objects in Layered Media, Applied Numerical Mathematics, to appear.

HONORS

D. S. Burnett, NSWC-PC, invited opening keynote address at the Comsol Multiphysics Conf., Boston, Oct. 23-25, 2005.